CEMENT AND LIME MANUFACTURE

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Effect of Cement Dust on Health.

AN exhaustive test on 2,278 employees in cement works in different parts of the United States has been undertaken by the Saranac Laboratory, and the conclusion is reached that there is no serious risk of disease as a result of exposure to cement dust. The following is from an abstract of the report of the Laboratory by Mr. A. J. R. Curtis, of the American Portland Cement Association, published in "Rock Products" for March, 1940.

An analysis of evidences of pulmonary tuberculosis indicates very definitely that prolonged exposure to moderately high concentrations of cement dust does not increase susceptibility to this infection. The combined incidence of all adult type tuberculous lesions, in both healed and active stages, is only 3·96 per cent. which is about one-third that reported for general population groups not exposed to dust. Likewise the evidence indicates that prolonged inhalation of finished cement dust has no unfavourable influence upon the course of an established tuberculosis. If it has any effect such dust seems to have reduced the anticipated number of active infections. Whether it has favoured calcification of healed lesions has not been definitely established. The mixed silica-containing dusts of the raw mills have neither increased susceptibility to tuberculous infection nor unfavourably altered its course.

Evidence of non-tuberculous infections of the lungs, found in less than 1 per cent. of the entire group, is no more common than in the general population. They occur at all ages and their incidence in different works is extremely variable. The fact that all of them, when discovered, were completely healed indicates that the inhaled dusts had exerted no unfavourable influence upon their course. They, in turn, had apparently failed to influence the localisation and resultant reaction to the inhaled dust, an outcome common with dusts of high silica content. The healed pleurisies were likewise unaffected by any coexistent pneumoconiosis.

In taking the medical histories, attention was given to bronchitis and other respiratory infections. There was a marked variation in the rate of bronchitis as well as other infections in cement workers in different parts of the country. These figures, based upon the statements of the men, may be subject to some error. Reports of low incidence in the dry sections of Texas and Kansas as contrasted with the high incidence in one of the dampest parts of New York State, suggest a marked climatic influence.

Variations in frequency of influenza, both epidemic and occasional, and of pneumonia were also undoubtedly modified by the general prevalence of such infection in each community.

The survey showed that finished cement dust is often present in relatively high concentrations in the atmosphere of the finishing mills and packing departments but this dust contains practically no free silica. In the raw mills and crusher houses the air contains variable concentrations of dust ranging from 1 to 30 per cent. silica, and in a limited area in one plant as much as 60 per cent. free silica on occasion, mixed with particles of limestone, shale, clay, and other materials. Technical obstacles prevented exact determination of the proportion of atmospheric silica that was present in inhalable state. It was shown, however, that much of it is too large to cause danger. In the quarries or mines blasting and loading operations produce dust, which in occasional cases may be high in free silica. The hazard in quarries is generally slight because the natural ventilation is good and the exposures are intermittent.

Of the total group of 2,278 persons examined, 1,979 were employed in the plants where they were exposed to dust of various kinds. The majority were white American males of slightly greater age distribution than in most industries. Exposures were generally prolonged; over 55 per cent. of the exposed group had worked in the cement industry more than ten years and nearly a third of them for more than fifteen years. Eighteen had been employed for more than forty-five years.

An exact correlation between exposure to the dusts of different compositions and the pulmonary conditions has been impossible because so many of the employeés have worked in several departments. Analysis indicates, however, that prolonged inhalation of dust from finished cement produces such slight anatomic reaction that little or no abnormality is seen in the roentgenogram. The mixed dusts of the raw mills, which contain free silica in varying amounts, are probably responsible for a limited number of cases of well-marked linear exaggeration which are non-disabling in character.

Only two individuals exposed to sandstone dust in special operations showed nodulation resulting from their employment.

When compared with the dust hazards in hard rock mining and other silica industries, the problem in the cement industry is trivial. The total incidence of first-degree linear exaggeration in the films of the cement group (15·09 per cent.) was less than half that in a group of rock miners, and for the second-degree the frequency (2·40 per cent.) was about one-thirteenth. Only eight of the 2,278

employees showed evidence of nodular fibrosis attributable to dust. In six of these exposure to silica dust in previous employment was presumably responsible. Two unusual cases (P_3) were also discovered in which infection, possibly associated with inhaled dust of some sort, was responsible for the roentgenographic patterns.

The incidence of tuberculosis and other chronic infections of the lungs was found to be less than that in the general population. The manifestations of tuberculosis occurred in typical form and at the same age periods as in persons not exposed to dust by occupation. It is concluded that prolonged inhalation of cement dust has no unfavourable influence upon susceptibility to tuberculous infection or upon its subsequent evolution.

Raw Materials for White Portland Cement.

FURTHER details about the new white Portland cement works at Carrara, U.S.A., which was mentioned in our issue for February last, are given in *Rock Products* for February 1940. A pilot plant of 50 barrels daily capacity is now in production. Tests have proved satisfactory, and plans are in progress for establishing a plant of 1,000 barrels daily capacity.

The principal raw materials are a white marble and a white silica-alumina clay, both of unusual whiteness and practically free from iron oxide and other objectionable compounds. Typical analyses of the raw materials, clinker, and cement are as follows:

	Marble	Clay	Clinker	Cement
SiO_2	0·96	71·86	27·22	26·50
Al_2O_3	0·00	13·04	5·60	5·59
Fe_2O_3	0·04	0·00	0·17	0·17
CaO	55·20	0·00	66·00	64·30
MgO	0·07	0·00	0·25	0·25
SO_3	0·00	2·80	0·00	1·67
Loss	43·60	12·10	0·13	1·38
Total	99·87	99·80	99·37	99·86

Cement—Initial Set, 3 hours 10 minutes. Final Set, 5 hours 10 minutes.
Clinker—Boiling test satisfactory.

In order to preserve the extreme whiteness of the materials, raw material elevators are of non-corrosive construction with rubber belting and galvanised buckets. The kiln is lined with 4-in. chrome-free bricks which are subjected to temperatures of about 2,800 deg. F. It has been found unnecessary to quench the clinker as it comes from the kiln. The hot clinker elevator is of special low-corrosion-factor metal and the ball mills are lined with flint pebbles for grinding.

The Carrara marble (limestone) deposit is almost pure calcium carbonate. The outcrop has a length of more than two miles, and a thickness estimated at 2,500 ft.

Froth Flotation in Cement Manufacture.

IN a paper read before the University of Michigan recently, under the auspices of the American Chemical Society, Mr. George K. Engelhart, of the Valley Forge Cement Company, dealt with the application of the froth flotation process in the cement industry. The following is an abstract of Mr. Engelhart's paper as published in the Cement Mill Section of *Concrete* (U.S.A.).

Limestones and other sources of lime, so contaminated by other minerals that they were considered unsuitable for cement manufacture, are now being used as the sources of raw material mixtures for the production of all known types of cement. The feature of the process which has made these materials suitable is the use of froth flotation, in which extremely small quantities of organic chemicals cause certain of the finely ground minerals to float and others to sink in water, whereby the undesirable minerals, or excessive proportions of useful minerals, can be separated and discarded. Some of the discoveries made during the development of this process may lead to the recovery or purification of other industrial minerals.

Several years ago Mr. Charles H. Breerwood, Vice-President of the Valley Forge Cement Company, discovered that, even though the chemical analyses of the mixtures remained constant, the cements produced from time to time varied widely in quality and strength. His investigations revealed that silica in its mineral form (quartz) did not react to form the essential calcium-silicates if the particles, although fine enough to pass through a sieve that would hold water, would not pass through a sieve having 325 openings per linear inch. Faced with the problem of removing these quartz grains from more than a thousand tons of ground rock a day, he experimented with the flotation process, which had previously been used principally for the recovery of precious metals and metal ores. It was found that if the material, suspended in about four times its weight of water, was agitated in a flotation cell in which was placed a small quantity of a fatty acid (the acids which form soap), grains of calcite (the mineral source of lime or calcium oxide) would float, whereas the other minerals would sink. The fatty acid forms a film, only one molecule thick, of insoluble metallic soap on the surfaces of the calcite grains, making them repel water but subject to the attachment of air bubbles which makes them float to the surface.

The other minerals are not filmed, and therefore sink. This made it possible to remove the coarse quartz, and also to correct the relation between the two principal constituents of an inferior rock. Methods were later developed to separate the settled minerals, whereby the proportions of all of the constituents could be corrected.

Although alumina is an essential constituent of cement, its proportion should be quite limited. Its common mineral forms in cement materials are the micas, kaolin, and feldspar. New reagents have been adapted to the process which float the minerals "upside-down" as compared with the others, causing these compounds to float away from the calcite and quartz, both of which are recovered, although the quartz must usually be reground to make it satisfactory for use.

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The use of these reagents has not been previously announced. Both types of flotation are now being used alone and in combination. Seven mills are now using the process.

Among the features of the process are the successful concentrations made from mixed minerals of extreme fineness, previously not thought to be amenable to concentration, and the recovery of industrial minerals of low intrinsic value, within the range of practical economics, and, with respect to the cost of cement manufacture, at a substantial saving.

Research on Pozzolana.

VOLCANIC ash, diatomites, clays, and other siliceous minerals are of importance as additions to concrete and mortar because of their ability to take up excess free lime. The kind and degree of combination of silica with lime, which forms the basis of use of these minerals, is imperfectly understood. A study of this combination, therefore, was undertaken by the U.S. Bureau of Mines from a phase-rule standpoint. This study is discussed by Mr. Oliver C. Ralston in report R. I. 3473 dated October, 1939.

After different methods were considered, a procedure involving reaction between lime and silicate ion in solution was developed. The precipitated calcium silicate was subjected to vigorous contact with different concentrations of lime, and the ratio of lime to silica in the solid and the respective concentrations in solution were measured at equilibrium.

The solid phases were hydrous and gelatinous throughout. To throw light on their structure, two physical-chemical methods were employed—adsorption isotherm and solubility product constant.

It was found that silica combines with calcium to give compounds that strongly adsorb lime. A Freundlich adsorption isotherm was obeyed by the two compounds so investigated. The maximum amount of lime held by the silica, including both chemically combined and adsorbed lime, was 1·45 mols CaO per mol of SiO_2, or 1·35 parts of lime per part of silica by weight.

It was deduced that the principal compound is, empirically, calcium metasilicate $CaO.SiO_2.aq.$, which exists in the range between 0·173 gm. CaO per litre and lime saturation or 1·1 gm. CaO per litre. This compound adsorbs up to 0·45 mol. of CaO per mol. of compound.

A second compound was deduced to be $3CaO.4SiO_2.aq.$, which exists in a narrow range of concentration between 0·0506 and 0·173 gm. CaO per litre. This material also adsorbs lime.

At a concentration of 0·0506 gm. CaO per litre a new solid makes its appearance—calcium disilicate, $CaO.2\ SiO_2.aq.$ This dissolves congruently in water. Hence the hydrolytic decomposition or extraction by water of calcium silicate in concrete continues only to the formation of calcium disilicate as a limit, and not, as is frequently supposed, to free silica as a limit. The latter can exist only when pozzolanic mineral is present in a greater amount than is required to form calcium disilicate.

Comparing Crystalline and Glassy Cements.

A BASIC hypothesis in the manufacture of cement is that the clinker, apart from some small residue of uncombined lime, reaches a state of chemical equilibrium in the burning zone of the rotary kiln, but that equilibrium is not maintained on subsequent cooling, says the January (1940) issue of "Highway Research Abstracts," published by the United States Highway Research Board in quoting from an article in the *Journal* of the Society of Chemical Industry.

At the hot zone, the clinker consists of a mixture of solid crystalline silicates and a molten liquid containing all the alumina and iron oxide together with lime, a small amount of silica, and the greater part of the remaining minor components of cement. On subsequent cooling the solid crystals and the molten liquid behave as independent systems, there being no reaction between the two as would be necessary to maintain chemical equilibrium. The rate of cooling will determine if the liquid is converted into a glass or into crystalline mixture.

It is desirable to know whether the physical properties of the cement are changed appreciably if the clinker contains glass or if it is completely crystalline. To determine this effect synthetic clinkers were prepared from samples of calcium carbonate, alumina, silicic and feric oxide of high purity mixed with water and compressed into briquettes weighing about 500 g., which were fired in a gas furnace. The resulting clinker was then ground and separated into two parts, and each part reheated to the original firing temperature for one hour. One portion was then quenched in water, producing a glassy clinker. The other portion was cooled slowly, producing a crystalline clinker. Samples of two commercial clinkers were also treated in this manner. The clinker resulting from this heat treatment was then ground to the desired fineness in a small ball mill with a predetermined optimum amount of gypsum.

The cements were then subjected to a number of tests to determine the effects of the heat treatment. Setting time was determined by the depth of penetration of a normal Vicat needle at different times. Soundness was determined with the Le Chatelier apparatus. Strengths were determined from 1 : 3 sand mortar cubes with ½-in. sides. Resistance to sulphate solutions, shrinkage, heat of hydration and other tests were also made.

From the data presented the following conclusions were drawn :

(1) The crystalline cements were easier to grind in the small-scale mills, but it is uncertain if this holds true under commercial conditions.

(2) Glassy cements give rise to no difficulty in controlling setting time, whereas some trouble was experienced with the crystalline cements.

(3) The crystalline cements had the lower heat of hydration.

(4) The glassy cements gave somewhat higher strengths at the age of 28 days.

(5) There is some evidence that the shrinkage of glassy cements may be somewhat lower than that of the crystalline cements.

(6) The glassy cements had a considerably higher resistance to attack by sulphate solutions than the crystalline cements.

Ball-Mill Grinding.*

Rod Mills with Different Ore Charges and Two Different Speeds in Batch Tests.—The continuous rod-mill tests were supplemented by batch grinding. Although 40 per cent. and 70 per cent. speeds have been found not to be the most desirable, they were used in tests to illustrate the effect of varying the charge. The results are shown in *Table* 9 (p. 104). In each of the two groups of tests the capacities and efficiencies increased progressively with decreased amounts of ore charge and were maximum at about 25 lb. By actual tests, 39 lb. of dry ore was required to fill the interstices at rest. The small amount required for best work indicates again that a large discharge on a rod mill is desirable. The observation that the wet rod milling was the best with a very small amount of ore is analogous to the dry ball milling shown in *Table* 14. A different trend is shown in the wet ball milling in *Table* 13.

Batch and Continuous Grinding Compared.—When the amount of ore in the mills was the same, no appreciable difference between batch and continuous open-circuit ball-mill grinding was found. This should be so, because the progression in particle size for the duration of a batch run would be expected to be the same as the progression from the feed to the discharge ends in a continuous run. *Table* 10 illustrates the marked similarity of the two wet-grinding methods. It includes tests with both chert and dolomite.

In examining the batch product of the dolomite, allowance should be made for the poor adjustment of the time period in the batch grind. The time should have been about 2·5 instead of 2·9 minutes. In other words the tons per horsepower-hour should have been greater, so that the reduction would have been somewhat less. In continuous work the rate of feed and size of discharge were adjusted so that each pair of tests had about the same amount of ore in the mill. If the pulp in the continuous tests had been extremely dilute, or if the continuous run had been in closed circuit, the products would have been different from the batch grind. When batch tests and continuous open-circuit tests are made with due consideration of fundamentals, the respective products may be expected to be identical.

Rods of Different Sizes and at Different Speeds in Open Circuit.—Rods of three sizes were tried in the open circuit at four speeds. The results are given in *Table* 11. The feed rate was adjusted as nearly as possible for a constant ratio with power. (Such adjustments are tedious, but they are worth the trouble.) It followed that the amounts of the subsieve material were about the same, and thus a comparison of size analyses and surface calculations is justified. As was expected, the largest rods gave the greatest capacity and efficiency and better selective grinding. Even the largest rods used might be too small for a large mill, because of the tendency of small long rods to become bent and subsequently entangled. Rods larger than 1·52 in. in diameter were not available.

* Continued from our April and May numbers.

TABLE 13.—BALL-MILL BATCH TESTS TO FIND OPTIMUM AMOUNT OF ORE IN [illegible] SPE[illegible]
(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speeds, as indicated. Load, [illegible] to 1 i[illegible]
60 per cent. solids.)

Size, mesh	Feed, weight percent cumulative	20 percent critical speed							40 percent critical speed							
		Pounds of ore in mill							Pounds of ore in mill							
		200	150	125	100	75	50	35	200	175	150	125	100	75	50	35
8	1.7	------	------	------	0.1	0.1	0.4	0.5	------	------	------	------	------	------	0.3	0.5
10	25.2	0.6	1.3	1.0	1.0	1.8	5.4	5.6	0.5	0.5	0.8	0.6	0.8	1.3	4.9	5.4
14	55.0	4.5	7.2	5.6	5.2	6.9	14.0	14.6	3.3	3.3	5.1	3.6	4.0	4.8	12.6	14.0
20	76.7	16.0	20.3	17.3	15.6	17.1	26.3	26.4	15.0	14.5	17.5	15.6	12.8	15.5	23.2	23.0
28	87.2	30.8	35.3	31.9	30.3	30.9	37.3	36.4	31.0	29.6	32.7	31.9	28.8	29.9	35.2	35.3
35	93.4	47.3	50.5	47.7	45.5	47.9	50.5	50.5	48.4	47.4	49.8	49.1	46.9	48.1	49.8	49.5
48	96.2	58.8	61.7	59.7	59.1	59.6	62.0	61.0	59.9	59.4	61.8	60.5	59.4	60.1	60.8	60.1
65	97.9	68.6	70.8	69.3	69.2	69.5	71.2	70.3	69.7	69.5	70.9	70.0	69.8	69.6	70.4	69.6
100	98.9	76.1	77.6	76.5	76.4	76.8	78.0	77.4	76.7	77.1	77.7	77.1	77.3	77.0	77.4	77.0
150	99.4	81.9	82.8	81.9	81.9	82.2	83.3	82.6	82.1	82.5	82.9	82.3	82.6	82.4	82.7	82.6
200	99.6	85.7	86.1	85.4	85.4	85.8	86.5	86.0	85.6	86.3	86.3	85.7	86.2	85.8	86.2	86.2
-200	.4	14.3	13.9	14.6	14.6	14.2	13.5	14.0	14.4	13.7	13.7	14.3	13.8	14.2	13.8	13.8
Surface tons per hour	------	11.1	12.4	12.8	13.2	13.5	13.8	13.4	14.8	15.5	16.7	17.4	18.1	19.3	19.8	19.5
Surface tons per horsepower-hour	------	22.7	22.4	22.1	21.8	21.4	21.4	21.1	22.5	23.5	23.3	22.6	22.0	21.6	21.4	21.3
Ton per hour	------	.090	.107	.105	.107	.112	.123	.117	.122	.129	.143	.146	.150	.160	.172	.168
Horsepower	------	.489	.551	.580	.606	.634	.643	.637	.622	.661	.717	.770	.824	.894	.925	.918
Ton per horsepower-hour	------	.184	.194	.181	.177	.177	.191	.184	.196	.195	.199	.189	.182	.179	.186	.183
Time, minutes	------	66.6	41.9	35.8	28.0	20.0	12.2	9.0	40.2	40.7	31.5	26.0	20.0	14.1	8.7	6.2
8	0.9	------	------	------	------	0.1	0.2	0.3	------	------	------	------	------	0.1	0.3	------
10	18.3	0.9	0.9	1.1	1.1	1.5	3.2	3.9	0.5	------	0.8	0.7	0.8	1.6	3.3	------
14	50.8	7.4	7.5	8.1	7.9	8.4	14.3	15.3	5.3	------	8.1	6.1	6.3	9.6	12.8	------
20	79.5	22.4	22.6	23.6	21.5	21.7	27.8	30.1	18.6	------	24.0	20.3	19.2	23.7	28.7	------
28	90.2	38.2	39.3	40.8	38.8	37.3	43.6	42.4	34.9	------	40.8	36.7	35.5	39.0	42.7	------
35	95.4	54.9	55.1	56.3	54.5	52.9	56.7	56.1	52.3	------	56.6	53.7	52.5	54.1	56.2	------
48	97.3	63.8	64.0	65.3	63.6	62.1	64.7	63.9	62.8	------	65.4	63.2	62.3	62.0	64.4	------
65	98.2	70.8	70.9	71.9	70.8	69.3	71.0	70.4	69.7	------	72.2	70.1	69.4	68.6	70.5	------
100	98.6	76.0	76.1	76.9	76.2	74.8	75.9	75.4	75.6	------	77.5	75.6	75.1	74.9	75.5	------
150	98.8	80.2	80.4	81.1	80.5	79.2	79.9	79.5	80.0	------	81.6	79.9	79.6	79.1	79.5	------
200	99.0	83.2	83.7	84.2	81.9	82.6	83.1	82.6	83.5	------	84.3	83.3	83.1	82.5	82.7	------
-200	1.0	16.8	16.3	15.8	18.1	17.4	16.9	17.4	16.5	------	15.7	16.7	16.9	17.5	17.3	------
Surface tons per hour	------	34.6	38.2	40.4	42.5	43.7	44.1	42.3	46.4	------	51.7	55.5	60.1	60.1	59.8	------
Surface tons per horsepower-hour	------	68.8	68.2	67.6	66.9	66.6	66.5	66.1	64.5	------	67.3	68.5	65.8	65.8	63.5	------
Ton per hour	------	.288	.321	.351	.357	.348	.375	.362	.375	------	.450	.453	.484	.484	.500	------
Horsepower	------	.507	.551	.598	.635	.655	.662	.654	.720	------	.768	.811	.914	.914	.942	------
Ton per horsepower-hour	------	.568	.583	.587	.562	.531	.566	.553	.521	------	.586	.559	.529	.529	.531	------
Time, minutes	------	20.8	14.0	10.6	8.4	6.5	4.0	2.9	16.0	------	10.0	7.9	4.6	4.6	3.0	------

SPEEDS: AT TOP TRI-STATE CHERT AND AT BOTTOM LEAD BELT DOLOMITE.
to 1 in. balls. Volume, 45 per cent. Ore charge, as indicated. Consistency,

	60 percent critical speed							70 percent critical speed							80 percent critical speed						
	Pounds of ore in mill							Pounds of ore in mill							Pounds of ore in mill						
35	200	150	125	100	75	50	35	200	150	125	100	75	50	35	200	175	150	125	100	75	50
0.2	--------	--------	--------	--------	0.1	0.1	0.1	--------	--------	--------	--------	0.1	0.1	0.1	--------	--------	--------	--------	--------	--------	0.2
4.5	0.2	0.5	0.4	0.5	1.8	2.2	2.1	0.3	0.2	0.3	0.2	1.1	2.2	2.0	--------	0.2	0.2	0.2	0.3	0.8	1.9
12.4	2.5	2.7	2.7	2.7	7.0	10.1	8.8	2.7	2.3	2.4	1.8	5.2	7.6	7.6	2.0	2.5	2.1	1.6	2.1	4.1	7.2
21.5	11.8	14.8	12.6	14.2	18.4	21.5	19.1	12.7	11.3	11.3	9.8	15.0	18.6	16.1	10.8	12.8	10.5	9.3	10.8	14.7	17.9
34.5	28.1	31.7	29.8	30.4	33.4	34.9	32.1	29.9	27.4	27.3	25.0	30.4	32.6	30.0	26.7	28.7	28.8	24.5	28.2	31.1	33.8
48.6	45.5	49.9	48.7	49.2	50.3	50.6	48.2	48.5	45.4	47.6	44.8	48.8	48.5	46.6	45.8	47.9	45.3	42.7	45.6	49.5	51.0
60.5	59.6	62.0	61.2	61.6	62.1	61.7	59.9	61.2	59.4	59.9	57.9	61.0	59.9	58.6	58.8	60.8	58.9	58.1	59.2	61.3	62.4
69.9	70.0	71.7	71.2	71.6	71.5	70.8	69.9	71.0	69.8	70.5	68.8	71.1	70.6	69.0	69.5	70.5	69.3	68.9	70.0	70.5	71.2
77.2	77.2	78.7	78.4	78.5	78.4	77.5	77.4	78.0	77.4	78.0	76.4	78.2	77.5	76.7	77.0	77.9	75.8	76.7	77.4	77.8	78.8
82.5	82.6	83.7	83.5	83.6	83.4	82.5	82.7	83.2	82.9	83.3	82.1	83.3	82.5	82.3	82.6	83.3	82.3	82.4	82.8	82.9	83.8
85.9	86.1	86.9	86.8	86.8	86.7	85.8	86.2	86.5	86.3	86.6	85.8	86.6	85.8	85.9	86.2	86.7	85.7	86.0	86.7	86.1	86.9
14.1	12.9	13.1	13.2	13.2	12.3	14.2	13.8	13.5	13.7	13.4	14.2	13.4	14.2	14.1	13.8	13.3	14.3	14.0	13.8	13.9	13.1
24.6	23.4	26.0	27.2	28.5	29.8	30.3	29.7	27.0	29.9	32.1	34.3	35.2	35.5	35.0	30.3	32.3	34.7	36.9	39.1	41.4	40.4
21.5	22.5	22.5	22.2	22.0	21.6	21.6	21.6	21.8	22.3	21.9	21.7	21.7	21.7	21.7	21.3	22.1	22.1	22.0	21.9	21.9	21.9
.200	.192	.228	.234	.248	.262	.261	.262	.223	.246	.270	.273	.308	.302	.288	.248	.273	.280	.296	.321	.352	.380
1.14	1.04	1.16	1.22	1.30	1.30	1.40	1.38	1.23	1.34	1.46	1.58	1.62	1.63	1.62	1.43	1.46	1.57	1.68	1.78	1.89	1.85
.184	.185	.197	.191	.191	.193	.186	.188	.186	.184	.184	.173	.187	.185	.178	.174	.187	.178	.176	.180	.186	.186
6.0	31.2	19.7	16.0	12.1	8.5	5.7	4.2	27.0	18.2	13.9	11.0	7.4	4.9	3.6	24.2	19.2	16.1	12.7	9.3	6.6	4.2
--------	--------	--------	--------	--------	0.2	0.2	--------	--------	--------	--------	--------	0.1	0.2	--------	--------	--------	--------	--------	--------	--------	--------
--------	0.4	0.8	0.8	0.8	1.3	2.6	--------	0.5	0.5	0.6	0.7	1.0	2.4	--------	0.5	--------	0.6	0.7	0.7	1.6	2.3
--------	5.8	7.1	7.0	6.8	8.8	13.1	--------	6.5	5.6	6.6	7.3	9.1	11.8	--------	4.9	--------	6.6	6.8	7.9	10.8	13.1
--------	20.3	22.8	22.2	20.9	23.4	28.9	--------	21.7	18.8	21.3	21.9	23.9	27.1	--------	21.5	--------	22.3	22.0	24.5	28.1	30.2
--------	36.9	39.8	38.8	37.2	39.1	43.3	--------	38.3	35.8	38.1	38.0	38.9	42.1	--------	38.0	--------	39.5	39.7	41.6	44.3	45.5
--------	53.4	55.9	56.5	53.6	54.7	57.2	--------	55.7	52.5	55.9	55.4	55.4	56.4	--------	55.3	--------	56.7	56.7	57.1	58.8	59.0
--------	63.7	64.8	65.6	62.8	63.7	66.1	--------	64.8	62.2	65.1	64.5	64.2	64.5	--------	64.3	--------	64.5	64.5	65.7	67.0	66.7
--------	69.5	71.2	72.0	69.2	70.3	70.8	--------	71.4	69.5	71.6	71.1	70.7	70.6	--------	71.1	--------	71.2	71.0	72.1	73.3	72.6
--------	74.8	76.3	77.2	74.4	75.6	75.8	--------	76.7	75.3	76.9	76.4	76.1	75.6	--------	76.0	--------	76.1	75.9	76.9	77.9	77.1
--------	79.0	80.4	81.2	78.5	79.9	79.8	--------	80.9	80.0	81.1	80.6	80.4	79.6	--------	80.1	--------	80.1	79.8	80.9	81.6	80.7
--------	82.2	83.6	84.3	81.8	83.2	82.8	--------	84.1	83.5	84.3	83.9	83.7	82.9	--------	83.2	--------	83.3	82.7	84.0	84.6	83.6
--------	17.8	16.4	15.7	18.2	16.8	17.2	--------	15.9	16.5	15.7	16.1	16.3	17.1	--------	16.8	--------	16.7	17.3	16.0	15.4	16.4
--------	72.2	80.9	86.0	93.9	93.9	88.7	--------	77.9	91.6	98.0	102	108	97.7	--------	86.0	--------	102	108	111	112	108
--------	64.7	65.5	69.0	67.3	62.0	58.1	--------	61.2	64.8	65.4	64.1	63.2	57.5	--------	56.3	--------	61.9	61.7	60.1	57.1	58.8
--------	.571	.694	.766	.735	.776	.750	--------	.666	.740	.844	.805	.886	.818	--------	.781	--------	.887	.888	.968	1.02	.917
--------	1.11	1.18	1.27	1.39	1.52	1.53	--------	1.27	1.41	1.50	1.59	1.70	1.70	--------	1.56	--------	1.66	1.75	1.85	1.96	1.91
--------	.513	.579	.600	.527	.513	.491	--------	.538	.528	.563	.543	.508	.481	--------	.488	--------	.518	.510	.538	.531	.479
--------	10.5	6.5	4.9	4.1	2.9	2.0	--------	9.0	6.1	4.5	3.5	2.6	1.8	--------	8.3	--------	5.2	4.2	3.1	2.2	1.6

TABLE 9.—ROD-MILL TEST AT 40 AND 70 PER CENT. CRITICAL SPEEDS.

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speeds, 40 and 70 per cent. critical. Load, 1¼ in. rods. Weight, 1,020 lb. Volume, 45 per cent. Ore charge, chert. Consistency, 60 per cent. solids.)

Size, mesh	Feed, weight percent	Products, weight percent															
		Pounds of ore in mill, 40 percent critical speed								Pounds of ore in mill, 70 percent critical speed							
		75	60	50	40	35	30	25	20	100	60	50	40	35	30	25	20
10	25.2																
14	55.0	0.2	0.3	0.9	0.1	0.6	0.8	0.1	0.1	1.2	0.4	0.1	0.1		0.6	0.3	0.8
20	76.7	8.6	12.3	12.7	7.0	9.9	10.9	5.1	4.4	20.3	10.8	10.6	10.9	5.8	12.3	10.1	12.6
28	87.2	31.2	33.9	33.8	26.4	29.5	29.4	21.8	18.7	42.7	29.3	29.5	29.1	22.2	31.6	27.3	28.2
35	93.4	52.7	54.0	54.1	48.5	50.4	50.3	44.8	42.8	61.0	52.9	52.5	52.0	46.5	52.2	48.4	51.1
48	96.2	64.7	64.8	65.4	61.2	62.8	62.8	58.7	57.1	71.1	65.1	64.6	64.1	60.1	64.0	60.9	63.6
65	97.9	73.6	74.4	74.8	71.7	72.4	72.5	70.1	68.4	79.0	74.6	74.1	73.7	70.8	73.4	71.0	73.8
100	98.9	79.9	80.6	81.1	79.0	79.3	79.4	77.5	76.2	84.2	81.2	80.7	80.4	78.2	80.1	78.3	81.0
150	99.4	84.4	85.0	85.6	84.2	84.3	84.5	83.0	81.9	87.8	85.7	85.4	85.3	83.6	84.8	83.7	86.[illegible]
200	99.6	87.2	87.8	88.5	87.4	87.5	87.6	86.5	85.6	90.4	88.5	88.4	88.4	87.0	87.8	87.0	89.4
−200	.4	12.8	12.2	11.5	12.6	12.5	12.4	13.5	14.4	9.6	11.5	11.6	11.6	13.0	12.2	13.0	10.6
Surface tons per hour		18.4	20.0	20.8	21.7	21.8	21.8	21.7	21.6	30.1	36.1	37.1	37.7	37.9	38.1	38.2	37.8
Surface tons per horsepower-hour		19.3	20.3	21.0	21.9	22.3	22.6	22.8	23.3	16.8	19.3	19.9	20.3	20.6	20.8	21.1	21.2
Ton per hour		.167	.188	.200	.188	.194	.195	.177	.167	.343	.343	.341	.343	.317	.350	.326	.360
Horsepower		.95	.98	.99	.99	.98	.97	.95	.93	1.79	1.87	1.87	1.86	1.85	1.83	1.81	1.78
Ton per horsepower-hour		.175	.191	.202	.190	.198	.202	.186	.180	.192	.183	.183	.185	.172	.191	.180	.202
Time, minutes		13.5	9.6	7.5	6.4	5.4	4.6	4.2	3.6	8.7	5.2	4.4	3.9	3.8	3.0	2.7	1.7

Although the rods were sized closer than is done in practice, a comparison of the work of rods and balls will be made. This may be done by taking the results of 60 per cent. speed and 45 per cent. rod volume from *Table* 11 and the same speed in the upper part of *Table* 13. The former is continuous and the latter is batch grinding, but this need not vitiate the comparisons. In the rod mill with the 1·52-in. rods, the tons per horsepower-hour were nearly the same as in the ball mill. The efficiency, that is, the surface tons per horsepower-hour, of the rod mill was a little below that of the ball mill.

These citations must not be taken to indicate that there is no difference between a rod mill and a ball mill. The former required more power[3] than the

TABLE 10.—BATCH GRINDING COMPARED WITH CONTINUOUS OPEN-CIRCUIT GRINDING.

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch and continuous, open. Discharge, 8 in. Speed, 60 per cent. critical. Ball load, Davis No. 1. Weight 796 lb. Volume, 45 per cent. Ore charge, chert and dolomite. Consistency, 60 per cent. solids.)

Size, mesh	Feed, weight percent	Dolomite no. 1, product, weight percent		Feed, weight percent	Chert, product, weight percent	
		Batch grind	Continuous grind		Batch grind	Continuous grind
8	0.9	0.2	0.1	1.7	0.1	0.2
10	15.3	1.3	2.1	25.2	3.2	3.8
14	50.8	8.8	13.3	55.0	10.1	12.1
20	79.5	23.4	30.2	76.7	21.5	22.7
28	90.2	39.1	47.3	87.2	34.9	37.0
35	95.4	54.7	60.6	93.4	50.6	51.1
48	97.3	63.7	68.4	96.2	61.7	61.4
65	98.2	70.3	74.8	97.9	70.8	70.7
100	98.6	75.6	79.4	98.9	77.5	77.9
150	98.8	79.9	83.1	99.4	82.5	83.0
200	99.0	83.2	85.9	99.6	85.8	86.4
−200	1.0	16.8	14.1	.4	14.2	13.6
Surface tons per hour		93.9	89.7		30.3	32.7
Surface tons per horsepower-hour		62.0	60.5		21.6	21.9
Ton per hour		.776	.879		.261	.288
Horsepower		1.52	1.48		1.40	1.49
Ton per horsepower-hour		.512	.593		.186	.193
Time, minutes		2.9	Continuous		5.7	Continuous
Ore in mill, pounds		75	73.4		50	51.6

latter when loaded with the same volume of media, and accordingly did more grinding. At 60 per cent. speed the 1·52-in. rods gave a capacity of 31·4 surface tons per hour, whereas the best capacity in the ball mill at the same speed (*Table* 13) was 30·3 surface tons per hour.

If an operator withdraws a ball charge and replaces it with the same volume of rods and then, on starting again, maintains the same feed rate, he will find that the effluent has a much smaller amount of coarse particles. Then, if he fails to take into account that he is doing more work on a unit weight of ore he will become an unduly ardent supporter of the rod mill. A just comparison cannot be made without taking power and feed rate into account.

Large Balls and Small Rods Compared.—Many investigators have attributed the selective grinding of rods to line contact. Other things should

[3] A unit volume of rods weighed 28 per cent. more than a unit volume of balls.

TABLE 11.—EFFECT OF ROD SIZE ON EFFICIENCY AND PARTICLE SIZE OF PRODUCT.

(Mill, cylindrical, 19 in. by 36 in. Circuit, continuous, open. Discharge, 4 in. Speed, varied. Load, rods, size varied. Weight, 1,020 lb. Volume, 45 per cent. Ore charge, chert. Consistency, 60 per cent. solids.)

Size, mesh	Feed, weight percent	Products, weight percent											
		40 percent critical speed			50 percent critical speed			60 percent critical speed			70 percent critical speed		
		Diameter of rods, inches			Diameter of rods, inches			Diameter of rods, inches			Diameter of rods, inches		
		0.94	1.25	1.52	0.94	1.25	1.52	0.94	1.25	1.52	0.94	1.25	1.52
8	1.7												
10	25.7	0.5	0.2	0.2	0.2	0.1	0.2	0.5	0.4	0.3	0.5	0.7	0.4
14	55.0	6.7	4.8	3.5	4.2	3.0	3.5	7.2	5.1	4.9	7.0	7.6	5.3
20	76.7	26.4	22.1	18.8	20.2	16.5	17.9	26.9	21.8	20.8	26.7	27.5	21.1
28	87.2	45.2	41.1	38.4	39.6	35.5	36.9	45.3	40.3	39.2	45.1	45.5	39.0
35	93.4	60.8	57.8	56.1	57.1	54.0	54.4	60.6	57.0	55.8	60.3	61.2	55.5
48	96.2	70.0	67.6	66.8	67.7	65.0	65.2	69.8	67.3	66.1	69.6	70.3	65.7
65	97.9	77.2	75.3	75.1	76.0	73.7	73.9	77.2	75.4	74.3	75.9	77.4	73.9
100	98.9	82.6	80.9	81.4	82.0	80.0	80.4	82.5	81.4	80.5	82.4	82.7	80.1
150	99.4	86.6	85.2	85.9	86.4	84.6	85.1	86.3	85.9	84.9	86.3	86.5	84.6
200	99.6	89.1	87.9	88.8	89.1	87.6	88.2	88.8	88.8	87.9	88.9	89.1	87.6
−200	.4	10.9	12.1	11.2	10.9	12.4	11.8	11.2	11.2	12.1	11.1	10.9	12.4
Surface tons per hour		14.8	18.5	18.8	20.7	25.2	25.9	26.0	30.0	31.4	30.1	32.5	36.4
Surface tons per horsepower-hour		16.0	17.5	18.3	17.1	18.9	19.0	17.6	18.4	18.9	17.4	17.1	18.7
Ton per hour		.162	.184	.188	.214	.236	.248	.282	.305	.305	.325	.357	.348
Horsepower		.925	1.055	1.029	1.211	1.336	1.363	1.477	1.628	1.667	1.729	1.901	1.942
Ton per horsepower-hour		.175	.174	.183	.177	.177	.182	.191	.187	.183	.188	.188	.179

be considered. In the two pairs of tests shown in *Table* 12 the relative deportment of large balls and small rods in batch wet grinding is shown. The two loads had the same volume. The rods required about 12 per cent. more power and their better selective grinding is obvious.

In considering the selective grinding of the rods, it must be remembered that the rods were heavier than the heaviest balls; they weighed 7 lb. each, whereas the largest balls weighed only 5 lb. each. On the basis of weight, the rods were larger than the balls although their diameters were much smaller. The rods, being only 35 in. long, may be regarded as much more rigid than rods

TABLE 12.—LARGE BALLS AND SMALL RODS COMPARED.

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speed, 60 per cent. critical. Ore charge, chert. Consistency, 60 per cent. solids. Load: Rod load—45 per cent. Volume, 145 rods of 0.94 in. average diameter, 1,020 lb. weight; ball load—45 per cent. volume, 796 lb. of 3 in., 2½ in. and 2 in. balls.)

Size, mesh	Feed, weight percent	Product, weight percent			
		50 pounds of chert		75 pounds of chert	
		Large balls	Small rods	Large balls	Small rods
8	1.7	0.1			
10	25.2	2.2		0.7	
14	55.0	10.2	1.3	5.3	1.4
20	76.7	24.2	12.8	17.6	15.6
28	87.2	40.2	33.7	34.8	37.7
35	93.4	56.9	54.5	53.3	57.4
48	96.2	67.4	66.5	65.2	68.3
65	97.9	75.6	75.3	74.3	76.3
100	98.9	82.0	81.9	81.1	82.5
150	99.4	86.3	86.3	85.8	86.7
200	99.6	89.0	89.0	88.7	89.4
−200	.4	11.0	11.0	11.3	10.6
Surface tons per hour		27.0	27.8	28.5	26.8
Surface tons per horsepower-hour		19.6	18.3	21.2	17.8
Ton per hour		.281	.281	.278	.278
Horsepower		1.38	1.521	1.343	1.506
Ton per horsepower-hour		.204	.185	.207	.185
Time, minutes		5.3	5.3	8.1	8.1

regularly used. These observations should be compared with *Table* 4, which shows that the heavier stuffed pipes did more selective grinding than the light pipes. There the diameters were the same, and selective grinding was due to the greater weight. Hence, weight as well as diameter of the medium has to be considered in appraising selective grinding and ball milling generally. When we theorise about angle of nip of media of different diameters we have to take density and weight into account.

Batch Ball Milling at Various Speeds and Ore Charges.—Chert, which is very hard, and dolomite, which is moderately hard, were selected for use in a study of the effect of different speeds and ore charges in batch tests. Mill, ball load, and pulp consistency were always the same. Results for chert are shown in the upper section of *Table* 13 (see pp. 102 and 103), and for dolomite in the lower. Each section is divided into six series and each series includes six or seven tests.

Usually the ore charges were 200 lb. to 35 lb., 72 lb. being the amount, as determined by test, required to fill the interstices of the ball load at rest. (In similar rod-mill tests, analysed in *Tables* 8 and 9, 39 lb. were required to fill the interstices.) When the great variety of speeds and sizes of charges is taken into account, the similarity of the size analyses is remarkable. The highest capacity in each series in the upper section was with an ore charge of from 50 lb. to 75 lb., but the highest efficiency was with an ore charge of from 150 lb. to 200 lb. The lower section, which is for dolomite, shows the same characteristics in a general way, but there is less spread between the charges required for best capacity and best efficiency. The broad spread of " time " in the different grinding periods should be noted with the similarity of the products. The time periods for grinding ranged from 66·6 minutes for the heavy chert charges at slow speed to 1·6 minutes for the light dolomite charges at high speed.

The tests indicate that for high capacity with the hard ore in continuous work a large discharge would be best, and that for efficiency a smaller discharge would be desirable. When the ore is softer, like dolomite, this distinction is not so important. The capacity increased with the speed, and when the ore charges were large the greatest efficiency was achieved at about 50 per cent. of critical. Although this speed was found to be best in some of the first tests, in which slipping was reduced by using a very short mill, it should be interpreted broadly as indicating a range rather than a specific setting. When the chert charges were small, efficiencies were about the same at all speeds, showing a small increase at high speed ; but when dolomite charges were similarly small, better efficiencies occurred at lower speeds. This difference illustrates how disputes can arise when experimenters draw conclusions from evidence that is too limited.

A common characteristic of the twelve series of tests is that the selective grinding of the coarse particles was better with a heavy ore charge. However, the grinding rate was low with these same heavy ore charges. It may be difficult to get the idea, but the tests indicate that, except for time spent in dumping and reloading, a batch wet mill would give the greatest output with a small ore charge.

In each series in *Table* 13 the highest point on the power curve usually coincided with the highest point on the capacity curve. This will be seen to be different in the dry grinding, as shown in *Table* 14 and *Fig.* 1. Under analogous conditions, the power for dolomite was higher than for chert ; at the respective speeds of 30 per cent. and 80 per cent. of the critical and with the same ore charges, the increase in power was about 4 per cent. One factor that contributed to this increase was the smaller volume of dolomite ; the ore charge was determined by weight, not by volume. The volume of a unit weight of dolomite was about 8 per cent. less than the same weight of chert. Another fact to be recorded is that at the end of the runs there was more coarse dolomite than flint. By referring to *Table* 5 it may be seen that the mean particle size affects power, and there also the maximum power was attained with the coarsest particle size.

Another factor to be considered is the type of grind. For a given charge of

dolomite the type of grinding is almost identical at all speeds. However, from a similar comparison of equal weights of the chert products it might be said that the high speed did give a little more selective grinding. These variables are mentioned primarily to call attention to the close accord.

TABLE 14.—DRY-BATCH BALL MILLING WITH VARIOUS ORE CHARGES (CHERT AT TOP AND DOLOMITE AT BOTTOM).

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speed, 50 per cent. critical. Ball load, Davis No. 1, 796 lb., volume, 45 per cent. Ore charge, chert and dolomite respectively. Consistency, dry.)

Size, mesh	Feed, weight percent	Product, weight percent						
		Pounds of ore in mill						
		200	150	125	100	75	50	35
10	25.2	1.7	1.4	1.8	1.3	1.2	1.4	2.3
14	55.0	3.3	8.1	8.4	6.6	6.0	6.2	8.7
20	76.7	24.3	21.1	22.1	18.0	17.2	16.5	21.0
28	87.2	39.8	36.4	37.6	32.8	32.1	30.7	34.2
35	93.4	52.6	49.8	51.3	47.1	47.1	45.4	48.7
48	96.2	62.8	60.6	62.4	59.1	59.9	58.2	61.1
65	97.9	70.6	69.0	70.7	68.2	69.5	67.9	70.5
100	98.9	77.6	76.4	78.0	76.2	77.9	76.4	78.5
150	99.4	82.0	81.2	82.6	81.4	83.1	81.8	83.5
200	99.6	85.5	84.9	86.1	85.3	87.0	85.8	87.1
−200	.4	14.5	15.1	13.9	14.7	13.0	14.2	12.9
Surface tons per hour		14.3	18.8	20.3	21.3	21.1	20.9	20.5
Surface tons per horsepower-hour		12.2	14.9	16.2	17.1	17.4	18.3	18.4
Ton per hour		.124	.155	.178	.173	.180	.169	.181
Horsepower		1.17	1.26	1.25	1.24	1.21	1.14	1.12
Ton per horsepower-hour		.106	.123	.142	.139	.149	.148	.162
Time, minutes		48.5	29.0	21.0	17.3	12.5	8.9	5.8
10	15.3	2.9	2.2	2.1	2.0	2.1	1.8	2.1
14	50.8	15.6	12.5	12.5	11.8	11.4	10.3	11.2
20	79.5	35.5	31.2	31.1	29.6	29.1	27.1	27.9
28	90.2	51.1	47.0	47.5	46.1	45.4	43.1	44.1
35	95.4	62.0	58.9	59.9	58.4	57.7	56.0	56.8
48	97.3	69.6	67.3	68.7	67.2	66.9	65.4	66.4
65	98.2	74.5	73.0	74.3	73.2	73.1	71.7	72.5
100	98.6	78.8	78.1	79.2	78.4	78.3	77.2	78.0
150	98.8	81.8	81.7	82.6	82.0	82.1	81.1	81.7
200	99.0	84.6	84.9	85.6	85.3	85.3	84.7	85.0
−200	1.0	15.4	15.1	14.4	14.7	14.7	15.3	15.0
Surface tons per hour		41.4	53.9	54.8	55.9	57.7	56.6	50.3
Surface tons per horsepower-hour		35.4	43.2	44.2	45.8	48.5	49.2	45.9
Ton per hour		.400	.500	.535	.521	.535	.500	.467
Horsepower		1.17	1.25	1.24	1.22	1.19	1.15	1.12
Ton per horsepower-hour		.342	.400	.431	.427	.450	.435	.417
Time, minites		15.0	9.0	7.0	5.7	4.2	3.0	2.2

Table 13 is valuable in connection with the old contention that high speed and impact are important. Certainly the record of efficiency does not support advocates of impact. At 30 per cent. speed the balls had only a slow, sluggish, rolling action, yet the grinding, when correlated with the power, was satisfactory.

In a given time, the batch mill, with about 75 lb. of ore charge, did more grinding than the mill with a lighter or heavier ore charge. This is proved by taking a given series and dividing weight by time, and also it may be seen in the table in the item "surface tons per hour."

Experimenters have been inclined to substitute number of turns of the ball mill for power readings and to speak of it as torque. They can find in *Table* 13 evidence to dissuade themselves of that practice. If the products of speed and time shown for the first four series of tests for dolomite are considered (in which the tests with 50 lb. are given), they will be found to be identical—120 ; that is, the number of turns was the same in each test. However, if power is similarly multiplied by time, the energy input will be seen to vary to a considerable degree. The number of turns is not always an exact measure of torque. The determination of power is the only accurate means of measuring torque.

Dry-batch Ball Milling with Various Ore Charges.—The tests shown in *Table* 14 were conducted on the two ores in the same manner as shown in *Table* 13, except that the grinding was dry and at only 50 per cent. speed. The percentage weight of products on the 14-mesh sieve shows only moderate changes in the type of grind ; in the wet grinding reported in *Table* 13 the heavy ore charge received selective grinding.

Capacity and efficiency were both maximum when the ore charge was 75 lb. to 50 lb. This capacity characteristic is like the wet grinding, but the high efficiency also with the same light ore charge is unlike the results of wet grinding, where a heavy ore charge was required for efficiency. That is, in dry grinding, the light ore charge was the best both as to capacity and efficiency. In this way dry grinding was like wet grinding in the rod mill, as shown in *Tables* 8 and 9.

The peak of the power curve shown in *Table* 14 at 150 lb. of ore is contrary to what would be predicted from the findings in wet grinding, in which the peak was reached with the small charge. In dry grinding it was a new experience to see the capacity curves and power curves of each series sloping in opposite directions instead of running nearly parallel as they did in wet grinding (see *Fig.* 1).

The dissimilarity of the power curves in wet and dry grinding may be examined by considering the amount of ore and water in the mill. The amount or volume of material filling the interstices between the balls in action has been shown to influence power, and it may be noted that the volume of a small amount of ore plus water, which required maximum power in wet grinding, is about the same as the volume of a large amount of dry ore, which had the same effect.

Dry-batch Ball Milling with Equal Ore Charges and at Various Speeds.—Having found from *Table* 14 that about 75 lb. gave the most advantageous dry charge, this amount was selected for runs at speeds from 40 per cent. to 90 per cent. of critical. The results are shown in *Table* 15. In a general inspection of this table, the 90 per cent. speed should be ignored after noting that the speed was too high. With that exception, the products for the different speeds are almost identical. Unlike wet grinding of chert in 75-lb. charges, in which the efficiency was about the same at all speeds, the maximum efficiency in dry grinding was attained at high speed. It is possible that the tendency of the dry charge to stick to the grinding medium at slow speeds reduces grinding efficiency. Although the best work was done at high speeds, nevertheless

the 90 per cent. speed was too high and illustrates how the work of a high-speed mill could be improved by reducing the speed.

Best Wet- and Dry-batch Ball Milling.—Capacities and efficiencies in wet and dry ball milling at different speeds and ore charges have been discussed. The results are summarised in *Table* 16, which shows that in both capacity and efficiency dry grinding was at its best with small ore charges and high speed. Likewise, in wet grinding the capacity was best with a small ore charge at high speed, but the efficiency was best with a large ore charge at slow speed. The numerical values inserted in the table are about 25 per cent. higher for wet grinding than for dry grinding. The values for capacity are more significant

TABLE 15.—Dry-Ball Milling at Various Speeds (Ore charge, 75 lb.)
(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speed, varied. Ball load, Davis No. 1, 796 lb. Volume, 45 per cent. Ore charge, chert, 75 lb.)

Size, mesh	Feed, weight percent	Product, weight percent					
		Critical speed, percent					
		40	50	60	70	80	90
10	25.2	1.9	1.3	1.1	0.9	1.2	2.6
14	55.0	7.7	6.0	6.0	5.3	7.1	2.3
20	76.7	18.8	17.2	17.8	17.2	20.2	28.5
28	87.2	32.8	32.1	33.5	32.7	35.6	44.2
35	93.4	46.7	47.1	48.4	47.5	49.7	57.1
48	96.2	58.9	59.9	60.8	59.2	61.2	67.3
65	97.9	68.4	69.5	70.0	68.5	69.8	75.1
100	98.9	76.8	77.9	78.1	76.5	77.3	81.7
150	99.4	82.2	83.1	83.1	81.8	82.2	85.9
200	99.6	86.1	87.0	86.8	85.7	85.9	88.9
−200	4	13.9	13.0	13.2	14.3	14.1	11.1
Surface tons per hour		15.9	21.1	26.6	30.5	33.0	30.7
Surface tons per horsepower-hour		16.2	17.4	18.7	19.1	19.2	11.4
Ton per hour		.132	.180	.231	.250	.281	.321
Horsepower		.988	1.21	1.42	1.60	1.71	1.61
Ton per horsepower-hour		.134	.149	.163	.156	.164	.119
Time, minutes		17.0	12.5	9.7	9.0	8.0	7.0

than those for efficiency. In considering efficiency values, it must be recognised that at a given speed and ore charge either the wet or dry grinding might not have been at its best. That is, it is not correct rigorously to compare the efficiency of wet and dry grinding without giving the mill the correct setting for each job.

The study of characteristics given in *Table* 16 may be carried farther in *Figs.* 1 and 2. The upper part of *Fig.* 1 shows that, in dry grinding, capacity and efficiency were best with a moderate ore charge; hence a large discharge is required. In wet grinding, also, capacity was best with a moderate ore charge, but a large ore charge was required for efficiency. The lower part of *Fig.* 1 shows that in wet grinding the power decreased with increased amount of ore charge but in dry grinding the power increased. In *Fig.* 2, in which the speed varied, the capacities increased with speed. The efficiencies changed only

moderately. As said before, the efficiency in dry grinding was a little better at high speed. The power curves at the bottom of *Fig.* 2 are typical of what has been shown before about power curves. The break of the power curve in dry grinding could have been predicted without completing the test at high

TABLE 16.—BEST WET AND DRY BALL MILLING.

Characteristics	Speed		Ore charge	
	Wet	Dry	Wet	Dry
Capacity	High	High	Small	Small
Relative surface tons per hour	(41.4)	(33.0)		
Efficiency	Low	High	Large	Small
Surface tons per horsepower-hour	(24.2)	(19.2)		

NOTE.—The figures in parentheses are for chert and they give the capacity and efficiency as taken from tables 13 and 15.

speed; the relatively high powers in dry grinding at 40, 50, and 60 per cent. speeds gave evidence of the excellent keying, which caused the balls to be thrown high. Hence they reached the 8-o'clock position at a lower speed than in wet grinding. In dry grinding the balls reached the 8-o'clock position at 80 per cent. speed, and thereafter the power dropped.

(*To be continued.*)

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